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SECOND QUARTERLY PROGRESS REPORT:

INVESTIGATION OF KILOVOLT ION SPUTTERING

by

HAROLD P. SMITH, JR. AND N. THOMAS OLSON

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-5743

SPACE SCIENCES LABORATORY
UNIVERSITY OF CALIFORNIA, BERKELEY

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October 31, 1964

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Technical Management
NASA Lewis Research Center
Cleveland, Ohio

Electronic Propulsion Office
Mr. Y. E. Strausser

SPACE SCIENCES LABORATORY
University of California, Berkeley

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ABSTRACT

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Electrostatic electron beam focussing techniques have been successfully applied to 2 to 4 kev cesium ion beam transmission. Normal bombardment of a neutron activated copper crystal (001 face) and gamma counting of the sputtered particles shows that the sputtering yield increases with ion energy from 8.9 atoms/ion at 2 kev to 14.5 atoms/ion at 4 kev. A quadrapole mass spectrometer has been combined with the ion source to successfully detect sputtered copper atoms. An ultra high vacuum system has been constructed and operated at 10^{-9} torr, and the pulse height spectrum of the spectrometer output has been measured.

Author

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INVESTIGATION OF KILOVOLT ION SPUTTERING

by

Harold P. Smith, Jr. and N. Thomas Olson

Space Sciences Laboratory, University of California, Berkeley

SUMMARY

This report is submitted as a second quarterly progress report on our efforts to investigate sputtering of copper and molybdenum by kilovolt cesium and mercury ion beams, as well as to develop a time-of-flight technique for the measurement of the neutral sputtered particle velocity spectrum.

Electrostatic electron beam focussing techniques have been successfully applied to the transport of heavy ion beams. It is shown that secondary electron contamination of the beam is unlikely and a simple experiment has been proposed to measure the effect. The cesium beam has been used to bombard a radioactive copper single crystal (normal bombardment of the (001) face). Gamma counting of the sputtered particles shows that the yield increases with ion energy between 2 and 4 kev (8.9 atoms/ion at 2 kev to 14.5 atoms/ion at 4 kev). The ion beam was also used to demonstrate that a quadrapole mass spectrometer can detect sputtered particles of copper atoms. Pulse counting of the spectrometer output has been demonstrated and the pulse-height spectrum of the electron multiplier output has been measured. It is shown that it is possible to discriminate against noise pulses so that only ion events are counted.

Additional equipment has been constructed and operated. These

include an ultra high vacuum system and an electrostatic deflection chopped cesium ion beam for operation in the ultra high vacuum system.

INTRODUCTION

Sputtering or ionic erosion of the accel electrode and focussing structure of the ion rocket engine can be the dominant mechanism limiting long term operation of the engine. Although the field of sputtering has been known since the phenomenon of gas discharge was first observed, no reliable theory to predict the yield, angular distribution, and velocity spectrum has been developed. Furthermore, it has only been within the past few years that experiments have been made under suitably defined conditions. In addition, there has been little work with either cesium or mercury beams so that it is difficult to predict the electrode erosion on the basis of previous data. For these reasons, the Lewis Research Center has sponsored detailed investigation of the sputtering of copper and molybdenum crystals under cesium and mercury ion beam bombardment where the target parameters such as temperature, angle of incidence, etc., are well known and varied over a large range of interest.

The University of California (Berkeley) Space Sciences Laboratory began an investigation of this field early in 1964. Four vacuum systems have been constructed to study these effects using radioactive tracer techniques to measure the yield and angular distribution and mass spectrographic and time-of-flight analysis to determine the velocity spectrum of the various sputtered particles. Although more equipment construction remains to be done, some preliminary measurements have been made and are reported here.

It is a please to acknowledge the valuable assistance of L. Stollar

and J. Fashin of the Department of Nuclear Engineering and D. DeMichele, M. Kosaki, R. Musket, and J. Radford, graduate students in the same department.

I. Cesium Ion Beam Transport

An electrostatic lens system for transporting heavy ions of kilovolt energies is described. The lens system is designed to use conventional D. C. high voltage power supplies to prevent space charge induced beam divergence while transporting an ion beam from its source to the region of intended use.

The design is based upon the analytical work of P. K. Tien*, who solved the equations of motion for an electron beam moving along the periodic potential of a series of annular rings. This geometry is illustrated in Fig. 1 where the trajectory of electrons on the periphery of the electron beam is indicated by the dashed lines. It is the object of each positive-negative lens pair to provide enough focussing action to compensate for divergence due to space charge effects.

For an electron beam of energy eV_o, Tien took the lenses to be biased with focussing potentials of $+V_f$ and $-V_f$. The electric potential, $V(r, z)$ is determined by the solution of LaPlace's equation. Tien then expanded the potential in a power series, and retained only the first two terms,

$$V(r,z) = F V_f \, I_0(\pi r/p) / I_0(\pi a/p) \qquad (1)$$

*P. K. Tien, J. of App. Phys., 25, 1281 (1954) where $F = \frac{2}{\pi}\left[\frac{\sin \frac{\pi}{2}(1 - S/P)}{\frac{\pi}{2}(1 - S/P)}\right]$ and $I_0(x)$ is the modified Bessel function of the zero order. This is a physically reasonable potential distribution since it is radially symmetric and periodic with period 2P.

Using this expression for the potential at a point r and z, it is possible to write the equation of motion. There are two forces acting on the electrons. On is that due to the electric field of the lenses. This force is given by $-eE = -e\frac{\partial V(r,z)}{\partial r}$. The other force is the mutually repulsive force from the rest of the electron beam. For a beam of current J_0 and mean velocity $\bar{v}_0$ (which is given by $\bar{v}_0 = \sqrt{2meV_0}$), the divergent force is $eJ_0/2\pi r_0 \epsilon \bar{v}_0$. Thus, the equation of motion is

$$\ddot{r} = -\eta\frac{\partial V}{\partial r} + \eta J_0/2\pi r_0 \epsilon \bar{v}_0 \tag{2}$$

where η is the electron charge to mass ratio.

By a change of variables and expanding V(r, z) in a Maclaurin series, the homogeneous part of the equation of motion can be rewritten as

$$\frac{d^2y}{du^2} - (2q\cos 2u)y = 0 \tag{3}$$

This is a form of the Mathieu equation and has the interesting property that to obtain a stable solution, the independent variables of the equation must obey certain equalities.

Tien shows that inhomogeneous equation of motion has the approximate particular solution

$$r = r_0 - (P/\pi)^2 \frac{V'}{2V_0}\cos \pi z/P \tag{4}$$

where

$$V' = \frac{\partial V(r,z)}{\partial r}\Big|_{r=r_0}$$

if

$$V'\left[V + V''\left(P/\pi\right)^2\right] = \left(\pi/P\right)^2 J_0 \sqrt{2V_0}/\pi r_0 \epsilon \sqrt{\eta} \qquad (5)$$

This is the condition between the parameters of the lens system to insure a stable particular solution.

The homogeneous solutions are, as mentioned above, Mathieu solutions and are stable if

$$\frac{P^2}{\pi^2}\frac{V''}{V} < .85$$

which is true for most situations including our particular case. The magnitude of the two Mathieu solutions are determined by the initial boundary conditions at the entrance to the lens system. In particular they are of zero magnitude if the beam is parallel at the entrance and if the charge distribution across the beam satisfies one of two conditions: (a) The charge is concentrated into a thin walled annulus, or (b) the charge is distributed according to the following condition,

$$j(r) = \frac{1}{2\pi r}\frac{dJ(r)}{dr}$$

where j(r) is the current density in amp/m^2 and dJ/dr is obtained by differentiating

$$J(r) = \frac{\pi r \epsilon}{\sqrt{2V_0/\eta}} V'\left(V + V'' P^2/\pi^2\right)$$

It is unlikely that either condition is satisfied by our cesium ion beam at the entrance to the lens stack, which is immediately downstream from the accel electrode. Hence, although the Mathieu solutions are stable, they may oscillate with an amplitude comparable to the inner diameter of the lens stack; thereby introducing inaccuracy in applying Tien's conditions (Eq. 5) to the transport of the cesium ion beam.

As was stated, Tien's work was for an electron beam. However, it is quite general and all that is necessary for using the analysis for ion beam work is to use the proper mass.

To find the lens system requiring the minimum focussing potential V_f, Eq. 5 was rewritten as

$$V_f = K I_c^{1/2} V_c^{1/4} \tag{6}$$

where K is a function of the physical dimensions of the lens system. Thus, to minimize V_f, K must be minimized.

The extractor electrode of the ion source used had a radius of 0.11" so that r_o was taken as this value. The lens radius was 3/16", and the lens thickness was 1/16". Using these dimensions, K was evaluated for various values of the lens pitch, P. The results are shown in Fig. 2. The minimum value of K occurred at a pitch of 1/4" so that the minimum focussing potential V_f is required when P = 1/4, r_o = 0.11, a = 3/16, and δ = 1.16.

Using these values in K, Eq. 6 becomes

$$V_f = 1.25 \times 10^4 I_c^{1/2} V_c^{1/4} \tag{7}$$

To check this analytical relation between the focussing potential, beam current, and ion potential, a lens system of the above dimensions was constructed and used to contain a cesium ion beam. The ion source was a porous tungsten-surface ionization source and is shown schematically in Fig. 3. The current transmitted by the lens stack was measured by two beam flags. The first was placed between the 2nd and 3rd electrodes, and the second was placed 5.5" downstream, between the 22nd and 23rd electrodes.

The current at the first beam flag during the experiments was 175 μa so that Eq. 7 would give the focussing potentials of Table 1 for the corresponding ion potentials.

The ability of the lens stack to hold the beam together was measured by the ratio of the current at the second beam flag to the current at the first beam flag. Experimentally, the current ratio was measured for ion energies of 1000, 2000, 3000 and 4000 volts. For each ion energy the focussing potential was varied from 0 to 3000 volts. The results obtained are shown in Fig. 4. From these results, it is apparent that the beam transmission is a maximum for a focussing potential of 3000 volts. This is not in exact agreement with Tien's analytical results tabulated in Table 1.

The reason for this disparity between the analytical and experimental results is not clear at this point. However, it is probably associated with the requirements on initial conditions at the lens stack entrance. The ions from the source most probably do not enter the lens stack parallel to the lens axis. In fact, this divergence was probably increased at the higher ion energies accounting for the very low transmission coefficients at 3 and 4 kilovolts ion energies and low focussing energies.

The entrance conditions to the lens stack is difficult to measure. However, computer programs to calculate the ion trajectories can be used to investigate this problem as well as to more exactly investigate the actual transport within the lens stack. We are currently in the process of adapting such a program to our own apparatus.

One area of particular concern in the transport of the cesium ion beam through the stack of lenses is the creation of secondary electrons by ion bombardment of a lens surface and the subsequent capture of the electron by the ion stream or the formation of cesium neutrals through recombination. Transport of the captured electrons can yield a fallacious reading for the total charge delivered to the target and therefore provide too high a value for the sputtering yield. The magnitude of this effect can be estimated by the following simplified model.

Assume that a free electron is created at the surface of a lens just outside that part of the ion beam transported through the lens as shown in Fig. 5. The force F_1 is the electrostatic force caused by the lens focussing potential, while F_2 is the space charge force of the ion beam which pulls the electron toward the stream. The ratio of these two forces is

$$R = F_2/F_1 = \frac{1}{8\pi\epsilon_0}\,\frac{P}{r_0}\,\frac{J_0\,(2M/E_0)^{1/2}}{V_p}$$

$R = .018$ using

$J_o = 100\ \mu a$

$V_p = 1500$ volts (8)

$P = .25$ volts

$r_o = .1$ volts

$M = 133$ amu

$E_o = 5$ kev

Hence, the force field seen by the secondary electron tends to prevent the electron from entering the ion beam.

A second consideration is the amount of electrostatic force needed to prevent the electron from moving with the ion beam if it should be captured by the beam. The energy of an electron moving with the same velocity as the cesium ion of energy E_o is

$$E_{electron} = E_o \frac{m_e}{M} \tag{9}$$

or, using the above figures,

$$E_{electron} = .02 \text{ ev}$$

Hence, secondary electrons cannot pass through the focussing potentials if moving at the ion beam velocity. However, those secondary electrons ejected from a negative potential lens in the direction of the ion stream could be accelerated through the potential field of the next positive lens and possibly strike the target.

Recombination of secondary electrons and cesium ions could also occur. The ratio of neutral current formed by recombination is estimated by

$$\frac{I\,(Cs^0)}{I_o\,(Cs^+)} = 1 - e^{-\sigma N L} \tag{10}$$

where

σ = recombination cross section

N = electron density

L = lens stack length $\approx$ .50 m

We conservatively estimate N by assuming that all cesium ions strike the lenses in the beginning of the stack and that each ion creates Y (taken as 2) secondary electrons in such a manner that the electrons continue in the beam direction with an energy $\ll V_i$, as discussed in the above paragraph. Then the number of electrons created per unit time and per unit volume is $J_0 Y / \pi r_0^2 L$. The electrons remain in the beam for a period of time equal to $L/(2eV_f/m_e)^{1/2}$

The electron density may then be taken as

$$N = \frac{J_0 Y}{\pi r_0^2 (2V_f e/m_e)^{1/2}} = 3 \times 10^{-12} \ cm^{-3} \tag{11}$$

The value of the recombination cross-section is of the order of 2×10^{-14} cm^2 *. Hence negliable recombination takes place.

The likelihood of significant error in measurement of the ion beam transmission as a result of secondary electrons being transported in the beam to the target is small, but the possibility cannot be excluded. For this reason, an experimental measurement of ion beam contamination by electrons and neutrals will be made during the next quarter.

II. Preliminary Measurements of Cesium-Copper Sputtering

The radioactive tracer technique has been developed to study the yield and angular distribution of copper atoms, sputtered from a single crystal by a cesium ion beam. Small discs of copper are spark cut from a single crystal of known orientation. The size of the disc is reduced to approximately 50 mg weight and 1 cm^2 area by chemical and electrical polishing. X-ray diffraction measurements show that the crystal is not damaged by these treatments and provide an accurate determination of the crystal orientation. Neutron irradiation to an activity of 1 mcurie provides sufficient sensitivity to measure 0.1 μg of sputtered particles

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*Marino, Smith, and Caplinger, Phys. Rev. 128, 2243 (1962).

on a 2π sterradian collector surface using a NaI gamma spectrometer. Orders of magnitude more sensitivity can be obtained by using smaller targets (i.e. increased specific radioactivity) and well shielded spectrometers. Preliminary yield measurements have been made for normal bombardment of the (001) copper plane using 2 to 4 Kev cesium ions. The yield S (atoms sputtered per ion) rises steadily with ion energy; from 8.9 at 2 Kev to 14.5 at 4 Kev. Care was taken to insure that the number of atoms sputtered from the surface was an order of magnitude greater than the arrival rate of vacuum contaminant gases and to prohibit secondary electron current from the target.

Although there is no data available in the literature that allows direct comparison of the above measurements, the yield coefficients are reasonable in view of the extensive work of Almen and Bruce* who studied the sputtering yield of monocrystalline copper under xenon (mass 131) bombardment in a higher energy range. Their work shows that the yield coefficient rises steadily with energy from 11 atoms/ion at 10 Kev to 20 atoms/ion at 50 Kev. They further show that the copper yield under krypton bombardment varies significantly (from approximately 5 to 30 atoms/ion) with crystal orientation. The variation with crystal orientation has also been noted by others; notably Southern, Willis, and Robinson** who noted a factor a three change in the yield of argon sputtered copper as a function of crystal orientation. We plan to include crystal orientation as parameter in our work during the next quarter.

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*O. Almen and G. Bruce, Nuclear Instruments and Methods 11, 279 (1961) and 11, 257 (1961).

**A. L. Southern, William R. Willis, and M. I. Robinson, J. Appl. Phys. 34, 153 (1963).

III. Preliminary Mass-Spectrographic Analysis of Cesium Copper Sputtering

A quadrapole mass spectrometer has been mounted and operated in a second vacuum system. The system operates at 4×10^{-7} torr and should go to lower pressures following installation of viton o-rings and higher system bakeout temperatures than have been attempted previously.

The cesium ion source (manufactured by the Hughes Research Laboratories, Malibu, California) which was used in the cesium-copper yield measurements described previously was mounted in the lower port of the system. The mass spectrometer was installed in a second port perpendicular to the ion source. A copper target with current monitoring apparatus was mounted at the intersection of the source and spectrometer lines-of-sight with angle of incidence equal to angle of reflection. The sensitivity of the spectrometer can be seen in Fig. 6 where the large peak is a result of cesium. Since the spectrometer ionizer was in operation, the cesium component shown in Fig. 6 resulted from both residual cesium and reflection of cesium ions.

The mass spectrum from 57 to 63 is shown in Fig. 7. The need for lower pressure (and reduced hydrocarbon partial pressure) can be seen from the peaks present at mass 63 and 65 where we would expect to measure the two isotopes of copper. Sputtering of the target caused the mass 63 and 65 to rise by a factor of 50% above the background. More detailed investigation was precluded by malfunctioning of the quadrapole electronics and the decision to return the ion source to its usual position for yield measurements. However, the results indicate that there should be no major problems in using the quadrapole mass analyzer to study the cesium-copper sputtering. It is felt that this work is useful for its own information as well as a necessary part of our effort to develop a time-of-flight technique for velocity measurements.

Our work in this regard can now proceed at a faster pace as a result of obtaining a second cesium ion source which was again furnished by the Hughes Research Laboratories.

IV. Electron Multiplier Pulse Height Analyses using 3300 Kev Sodium Ions

An electron multiplier, which is the same as the mass spectrometer multiplier, has been installed in the third vacuum system. A tungsten filament is heated to temperatures sufficient to boil off alkali impurities. The power supply necessary for this is a DC device especially constructed to reduce 60 cps pickup from the filament by the EM (Electron Multiplier). The filament is shielded from the multiplier by a grounded copper hood. A 1/8" hole is provided to allow ions produced at the filament surface to reach the EM. The filament is then heated while the power supply and filament are floated at +300 volts to suppress thermal electron currents from the filament and to accelerate alkali ions emitted from the filament towards the multiplier. The first dynode of the multiplier is held at -3000 volts with the anode at ground. Pulses are noted by dropping the output anode current through a 1 megohm resistor and reading the voltage across the resistor on a high speed sensitive oscilloscope. The schematic of this apparatus is shown in Fig. 8.

Single pulses of electron current from the anode are shown in Fig. 9. They are of the order of 5 mv (when the current is dropped through a 1 megohm resistor) with a rise time on the order of 1 microsecond. Evidence that the pulses were induced by ion bombardment of the first dynode of the multiplier was noted by the fact that the pulses were discontinued when the filament voltage was changed to from +300 v to -300 volts. In the latter case, it is impossible for the alkali ions boiled from the filament to be transmitted through the shield which is held at ground.

As shown in Fig. 8, the pulses from the anode were sent to a pre-amp and then to a double differentiation amplifier. The amplifier pulse output is shown in Fig. 10 where it can be noted that the pulse width is essentially one microsecond and that the effect of the slow fall time of the original pulse has been eliminated by double differentiation.

The train of amplified pulses were then sent to a 400 channel RIDL pulse height analyzer (PHA). The results are shown in Fig. 11. The PHA discriminator was set at its lowest value, but even in this setting, no pulses were stored in channels 1 through 4. Storage in all other channels decreased monotonically with voltage height (i.e. channel number)*. If the ion gate was closed, as described above, no pulses were stored in the PHA. It had been hoped that the 3.3 Kev particles would eject sufficient secondary electrons from the first dynode to cause a peak to occur in the pulse-height spectrum. Evidently, higher energies are needed and could be obtained simply by floating the filament at a higher voltage. However, this conditions would not correspond to the conditions under which pulse counting will be used; viz. mass spectrometer output. Higher voltages could be obtained in the latter case by operating the electron multiplier with a larger voltage drop, but operation above 3.5 kv exceeds the specifications of the device.

It is sufficient for our purposes to insure that the ion induced voltage pulses are higher than noise pulses which seems to be the case. A peak

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*There is a slight peak observable at 4.5 mv. This fluctuation is greater by a factor of three than expected from Poisson counting statistics, but it still appears to be too small for significant consideration.

on the pulse height spectrum would have been interesting, but it is not necessary for operation of the spectrometer output in the pulse count mode.

V. Construction and Operation of an Ultra-High Vacuum System

As noted in Fig. 7, the current mass spectrometer output when operated at 4×10^{-7} torr has a significant background output in the mass 63 through 65 range. This may be attributed to the hydrocarbon content of the vacuum system which is pumped by an oil diffusion pump and currently uses standard buna o-rings. An estimate of the number of ionized background contaminants at mass 65 can be made by assuming that the multiplier gain is 10^5. The voltage is determined by the multiplier output when dropped through a 1 megohm resistor. Hence, we estimate a current of approximately 10^5 ionized particles/sec background at mass 63. Although it may be possible to tolerate this level in the time-of-flight measurements, it would be far less difficult if the contaminants in this range were reduced.

This is accomplished by construction of an ultra-high vacuum system. All parts are bakeable (including the mass spectrometer) to $400^{\circ}C$. All seals and valves use metal gaskets. In particular, we have used rotatable knife-edge sexless flanges, which use standard 1.5 mil aluminum foil as the gasket material. These flanges are manufactured using standard machine shop equipment. No leaks have been measured in this system using both a helium leak detector and a vac-ion pump leak detector. Bakeout to approximately $150^{\circ}C$ and continuous 200 liter/sec vac-ion pumping reduced the system pressure to 2×10^{-9} torr as measured by a nude ion gauge at the furthest point in the chamber from the pump.

The chamber has been disassembled for chemical emersion cleaning before going to higher bakeout temperatures. Following reassembly and high bakeout, it is expected that the system will operate in the low 10^{-10} torr region. If this is the case, the contamination reduction at mass 60 through 70 range should be significant since (a) the overall pressure has been reduced and (b) the potential sources of hydrocarbon contamination have been removed by using vac-ion pumping and all metal parts.

The chamber has been supplied with a variable leak valve and four access ports including a special port for the mass spectrometer. A second port will mount a cesium ion source which is described in a following section. The other two ports are for the target assembly and electrical and cooling feedthroughs.

VI. Mercury Ion Beam Sputtering

The vacuum system used for the pulse counting experiments is being converted to the pumping system for a Thompson-Ramo-Wooldridge (TRW) mercury ion source which has been ordered. Unfortunately, as a result of administrative difficulties between the University of California and TRW it was not possible to issue a purchase order until the middle of October. For this reason, delivery of the ion source is not expected until the end of the present calendar year. Obviously, there can be no useful measurements until the ion source has been delivered and accepted.

VII. Construction and Operation of a Chopped-Beam Cesium Ion Source

A surface contact cesium ion source using electron bombardment heating of the porous tungsten tip has been constructed and successfully operated at 1 ma current. The source is insulated from, but mounted to, a metal sealing flange (described in section V) suitable for operation on one port of the ultra high vacuum system.

A two dimensional electrostatic deflection system is mounted just downstream of the accel electrode and serves the dual purpose of steering and chopping when used with an additional collimator immediately downstream from the deflection plates. Initial measurements indicate that a 2 Kev cesium beam can be successfully chopped with this device and should be suitable for the time-of-flight measurements. Further testing was postponed following the formation of a crack between the molybdenum sleeve and the tungsten tip. A second sleeve and tip assembly is available and will be used as a replacement.

VIII. STATEMENT OF FINANCES

On Account: 1-489580-26302 Kilovolt Ion Sputtering

Period Ending: September 30, 1964

	Approp.		9/64	To Date	Unexpended Funds	Obligations	Balance Available
General Assistance	$34,696.00	$7,173.13	$1,924.30	$9,097.43	$25,598.57	$13,470.10	$12,128.47
Employee Benefits	1,854.00	358.66	192.43	551.09	1,302.91	1,347.01	(44.10)
Supplies and Expenses	10,100.40	1,876.80	889.55	2,766.35	7,334.05	780.81	6,553.24
Equipment and Facilities	30,100.00	8,394.20	3,325.79	11,719.99	18,380.01	2,433.45	15,946.56
Overhead	11,450.00	2,367.12	635.02	3,002.15	8,447.85	4,445.12	4,002.72
	$88,200.40	$20,169.92	$6,967.09	$27,137.01	$61,063.39	$22,476.50	$38,586.89

Date of Contract: April 18, 1964

Termination Date: April 17, 1965

Prepared by: Harold McPherson

Date: October 12, 1964

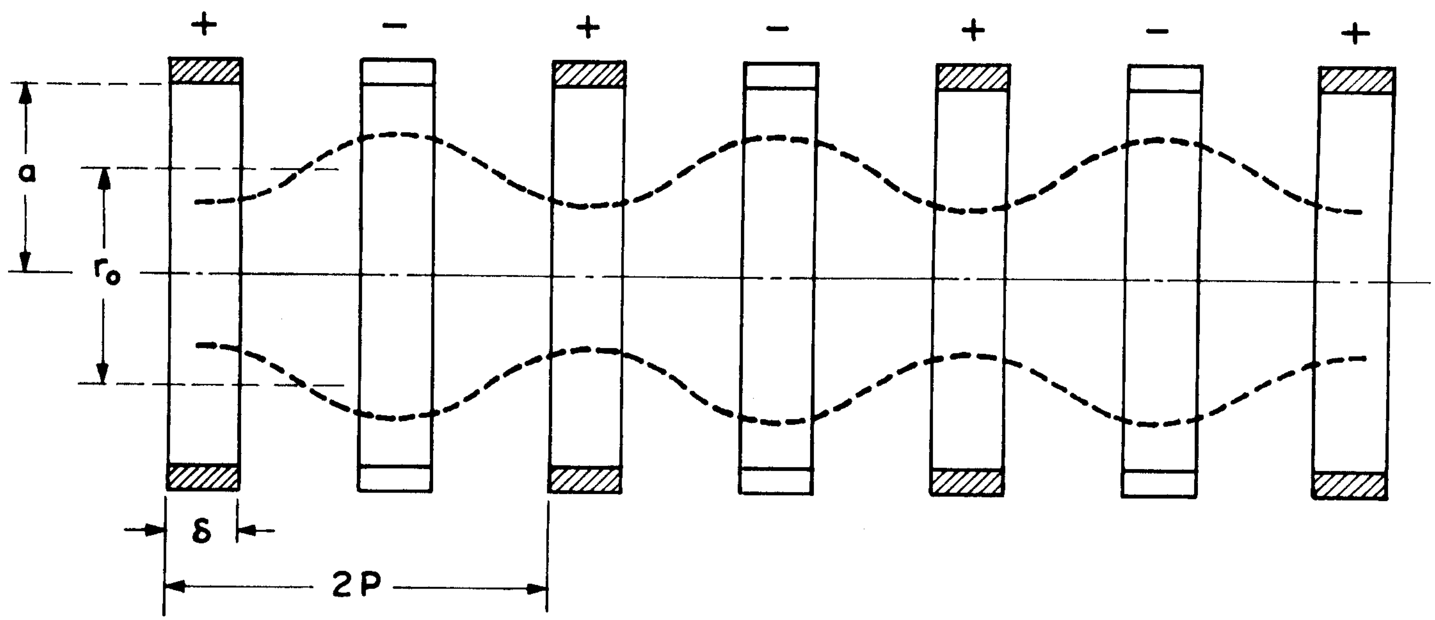
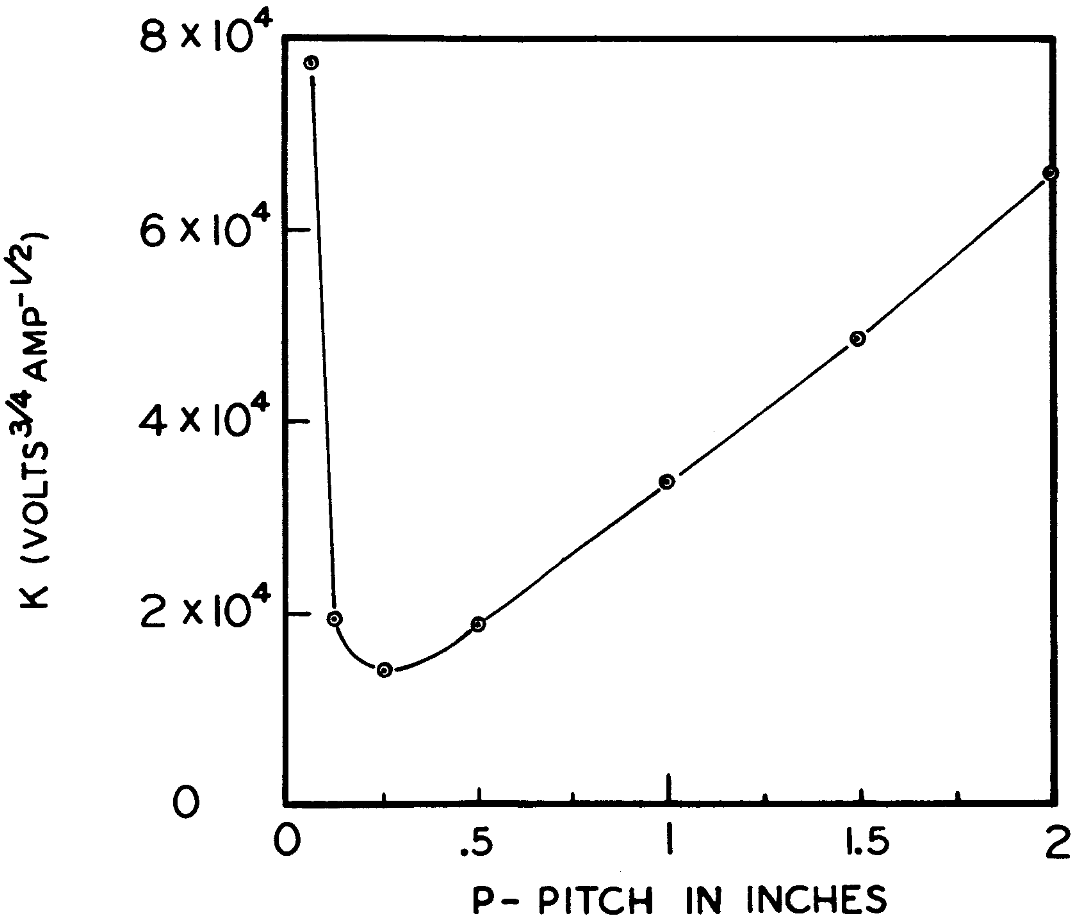


Figure 1


8 x 10^4
6 x 10^4
4 x 10^4
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K (VOLTS^3/4 AMP^-1/2)
0
.5
1
1.5
2
P- PITCH IN INCHES

Figure 2

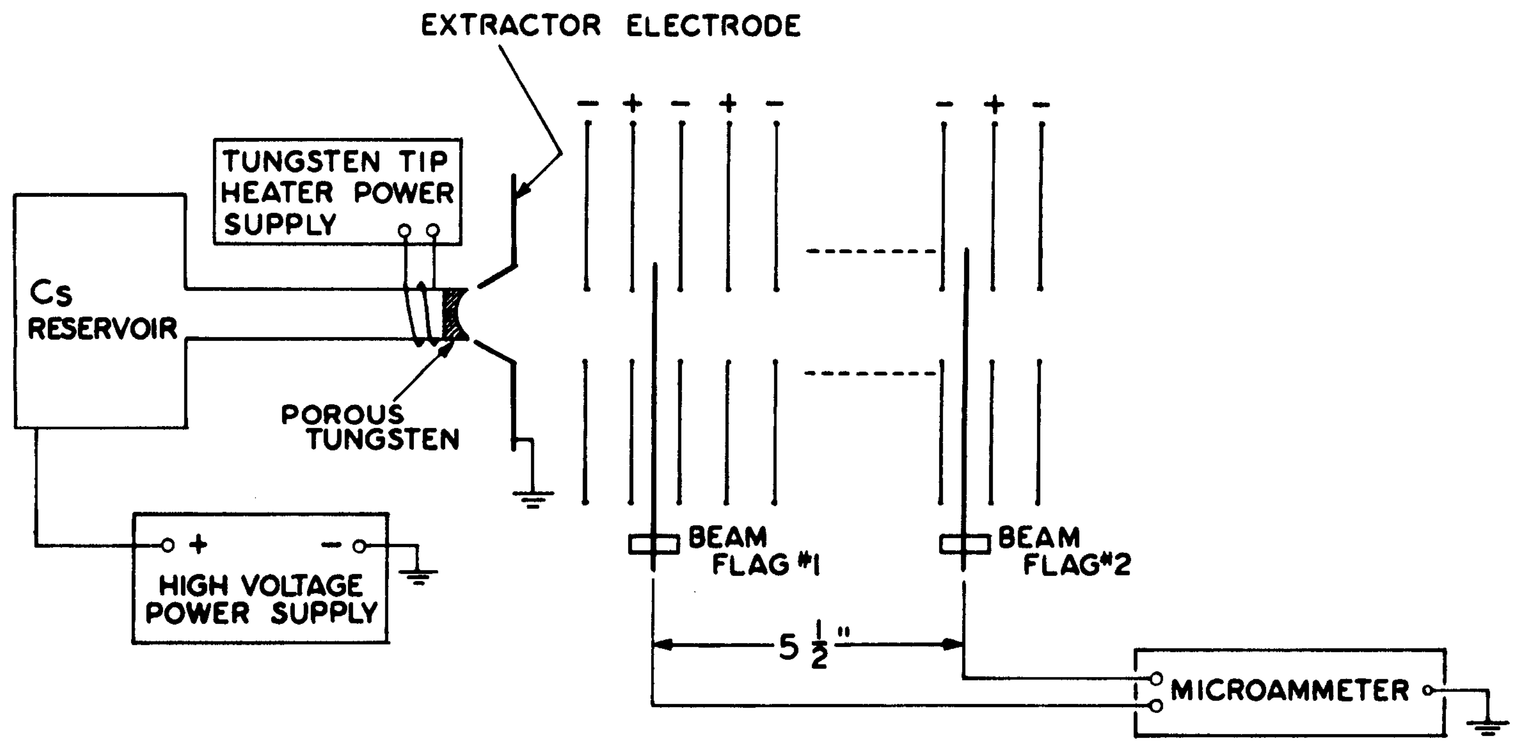
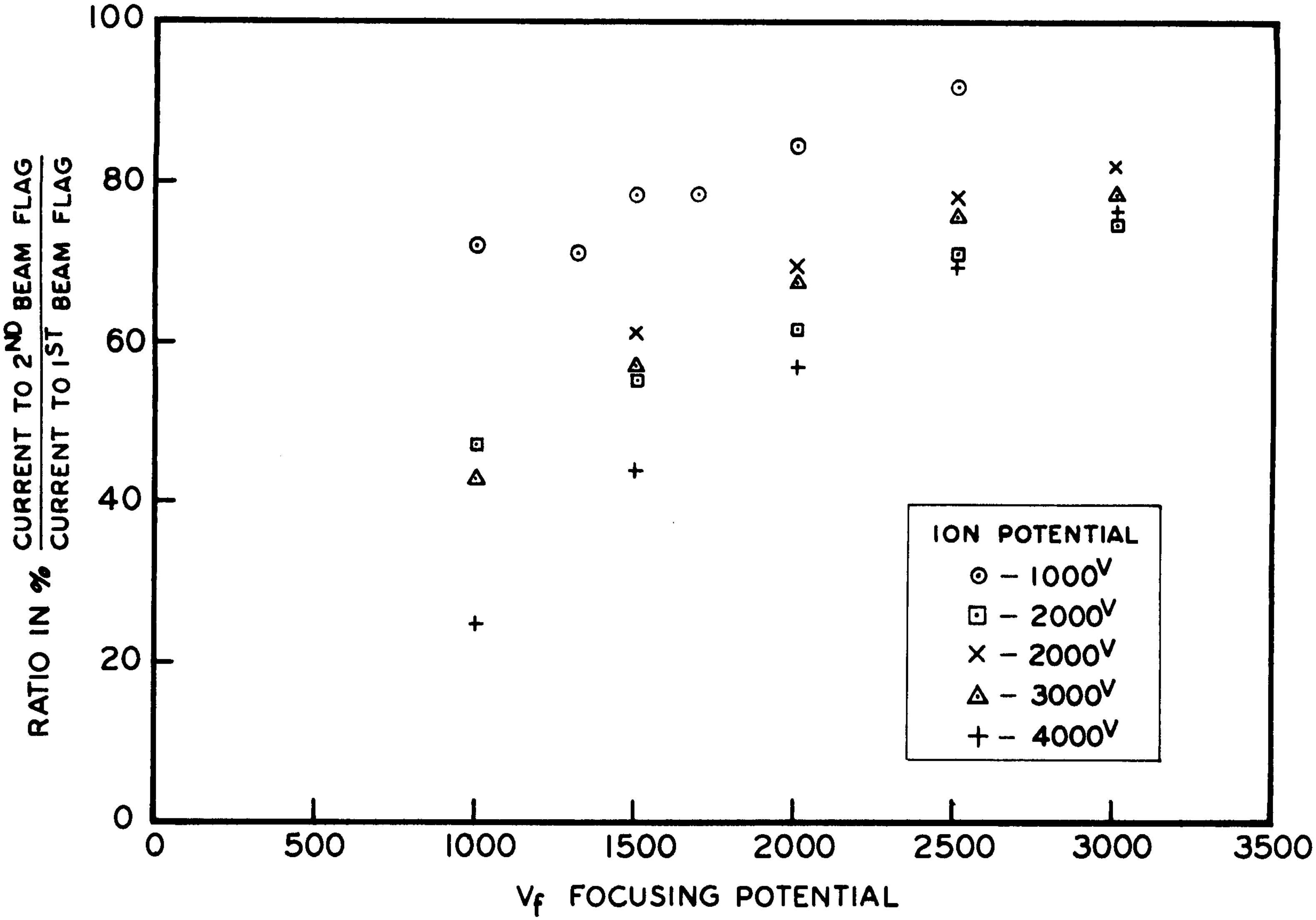

EXTRACTOR ELECTRODE
TUNGSTEN TIP HEATER POWER SUPPLY
Cs RESERVOIR
POROUS TUNGSTEN
HIGH VOLTAGE POWER SUPPLY
BEAM FLAG #1
BEAM FLAG #2
5 1/2"
MICROAMMETER

Figure 3



100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
RATIO IN % CURRENT TO 2ND BEAM FLAG / CURRENT TO 1ST BEAM FLAG
ION POTENTIAL
⊙ – 1000V
⊡ – 2000V
× – 2000V
△ – 3000V
+ – 4000V
Vf FOCUSING POTENTIAL

Figure 4

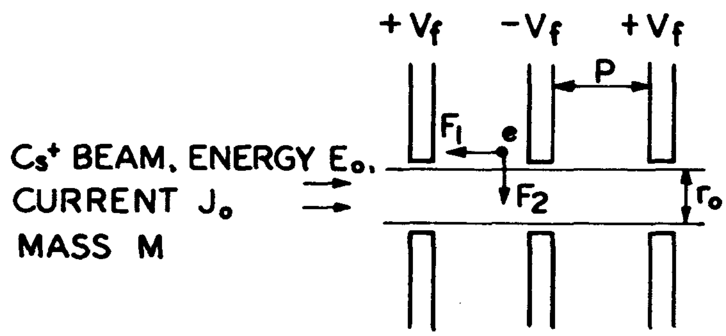


Figure 5 Electrostatic and space charge force on a secondary electron in a alternating potential focusing structure

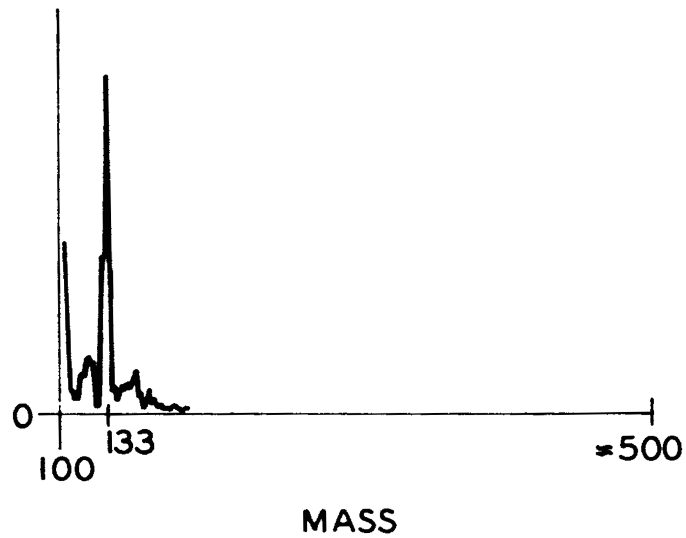


Figure 6 Cesium-Copper spectrum above mass 100 showing mass 133 (Cesium)

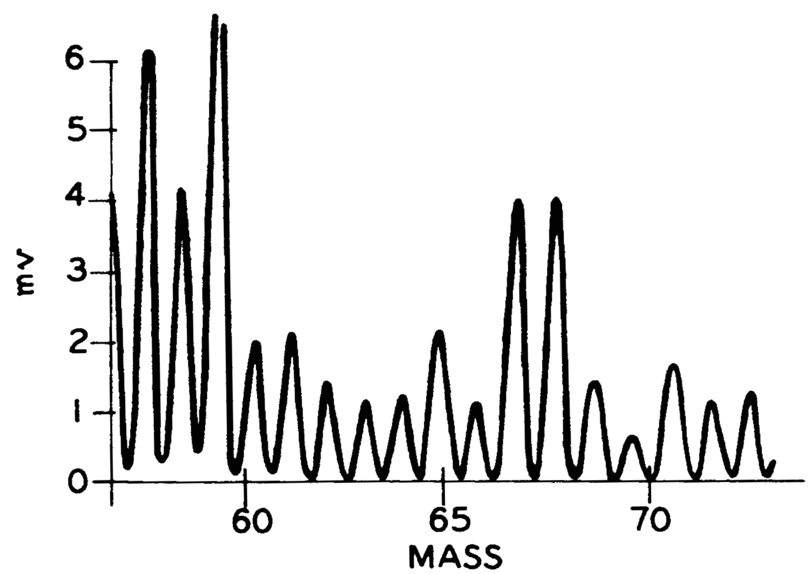


Figure 7 Cesium-Copper spectrum from mass 57 to mass 73

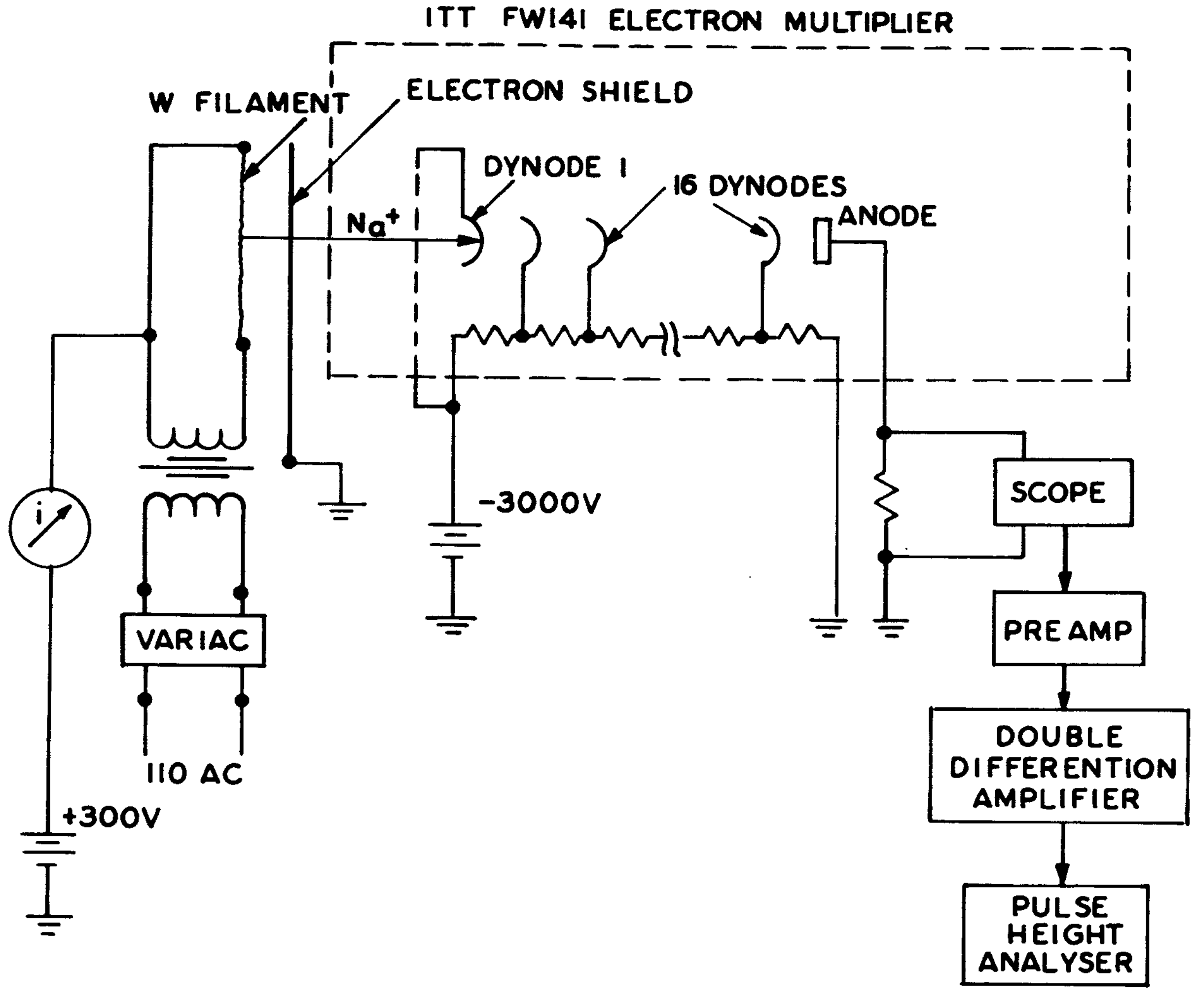


Figure 8 Schematic of Pulse Count Apparatus

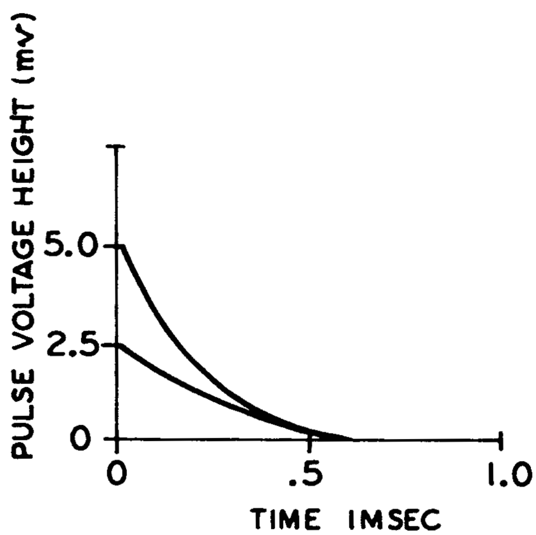


Figure 9 3.3 kev ion induced electron multiplier pulses

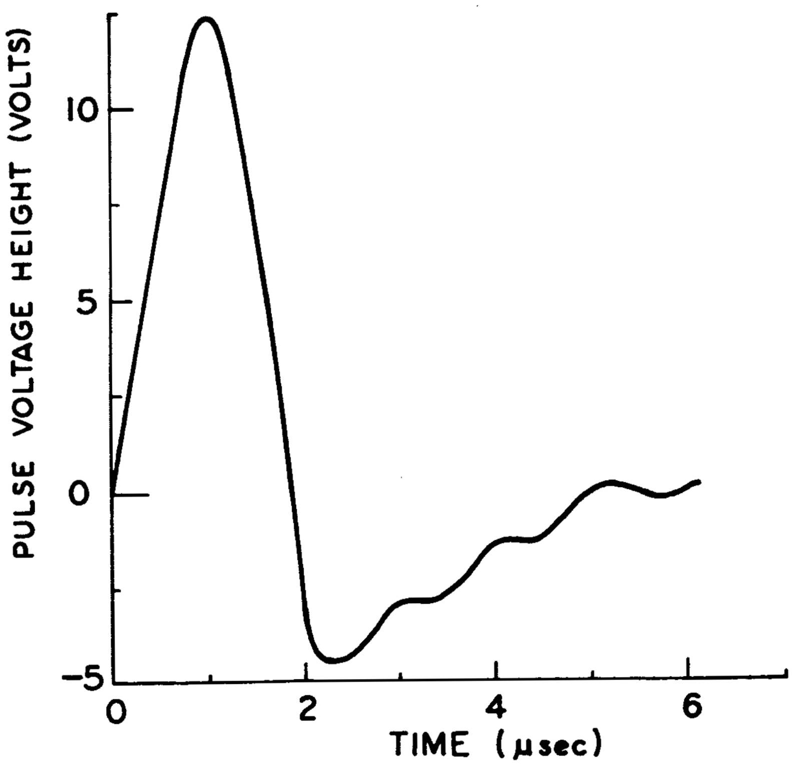


Figure 10 Amplified and differentiated electron multiplier pulse

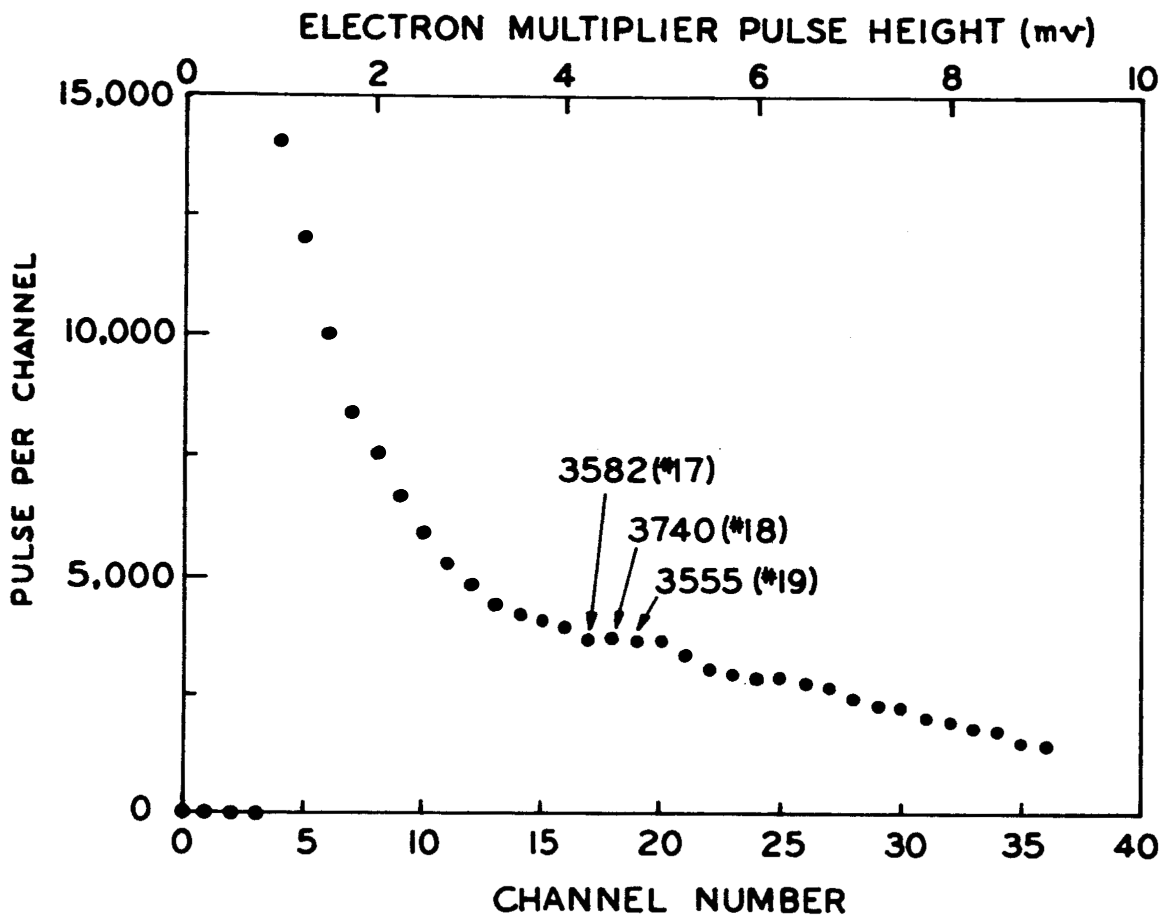


Figure 11 Pulse height analysis of 3.3 kev ion induced electron multiplier pulses